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A CONTINUOUS WAVE RAMAN LASER TO ACCESS A BROAD SPECTRAL REGIME

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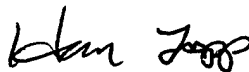Contract Number: F33615-99-C-1485
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13. ABSTRACT *(Maximum 200 words)*
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The purpose of this work was to explore the continuous wave (cw) Raman laser for generating high-power laser radiation in the Infra-Red (IR) spectral regime. This was done by numerically modeling cw Raman lasers. The numerical models were compared with results from recent experiments to confirm their accuracy. A survey was conducted to identify necessary components for this technology, including mirrors and pump lasers. Results indicate that the cw Raman laser can produce useful low-power laser radiation across the spectral range from 1 μm to 5 μm using commercially available diode lasers as pumps. Available pump lasers limit the ranges of wavelengths that can be produced at high-powers. Using real-world parameters, theory indicates photon conversion efficiencies of approximately 90% are possible. Independent experimental measurements have recorded efficiencies of over 60% without achieving optimal operating conditions. Additionally, the laser can be built to be compact, with longest dimensions on the order of 10 cm. Potential applications of the cw Raman laser include generation of high-power eye-safe radiation, generation of high-power mid-IR laser radiation of IR countermeasures, and generation of a broad range of mid-IR wavelengths for spectroscopy applications.

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A Continuous Wave Raman Laser to Access A Broad Spectral Regime: Phase I Final Report

a. Introduction and Review

This SBIR Phase I effort was devoted to the development of the off-resonant cw Raman laser. The cw Raman laser is a new laser that promises to deliver stable, high-quality, moderate to high-power laser beams in the near to mid-IR spectral regime, including the so-called molecular finger-print spectral range of 3 μm to 5 μm. [1-4] This laser is efficient, does not require cooling, and can be built small enough for a person to hold it in his or her hand.

The cw Raman laser is an optically pumped laser that shifts the frequency of the input "pump" laser frequency by an amount determined by the molecular energy levels of the Raman medium. One of the primary advantages of this technology is that it can be used to generate laser beams at frequencies that are difficult to obtain otherwise. Additionally, efficient diode lasers can be used as pumps. Tuning ranges of 40 nm have recently been demonstrated using a diode laser as a pump. [5] The frequency ranges that can be obtained with diode laser pumps using hydrogen and methane as Raman mediums are shown in figure 1.
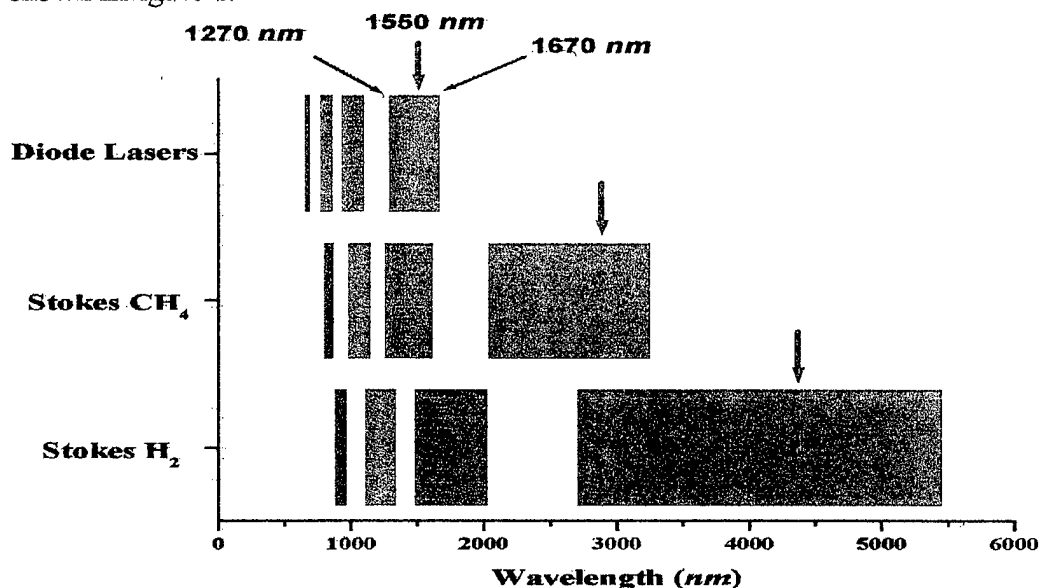

Figure 1. Spectral ranges of frequency shifted (Stokes) radiation accessible using diode lasers as pumps from Raman scattering in methane and hydrogen.

A further advantage of the cw Raman laser is its efficiency. For real-world parameters, photon conversion efficiencies of 90% have been predicted, and experiments performed in the laboratories of Prof. John Carlsten at Montana State University have obtained approximately 65% photon conversion efficiencies, even without operating at optimal pump powers. The significance of this high efficiency is that the development of high-power pump lasers in the near IR spectral regime will directly lead to high-power lasers in the mid-IR using the cw Raman laser.

A schematic of the typical components of the cw Raman laser is shown in figure 2. A pump laser provides energy. Within the Raman cell, pump photons scatter in an inelastic manner from Raman active molecules. This produces lower energy (red-shifted) photons, referred to as "Stokes" radiation, and leaves the molecules in an excited state. This pump laser must be efficiently coupled into a high-finesse cavity that contains a Raman active material, such as hydrogen or methane. The gain for Raman scattering depends on the material, the pump laser intensity within the Raman active material, and on the length of interaction in the Raman active material. Efficient Raman scattering occurs within the high-finesse cavity for two reasons: 1) The intensity of the pump laser within the high-finesse cavity is increased by roughly a factor of the finesse of the cavity at the pump wavelength; 2) The effective overlap distance of the pump and Stokes beam is increased by roughly a factor of the finesse of the cavity at the Stokes wavelength. The two effects together can increase the gain by more than eight orders of magnitude as compared to a "cavityless" situation, thereby leading to efficient frequency conversion.
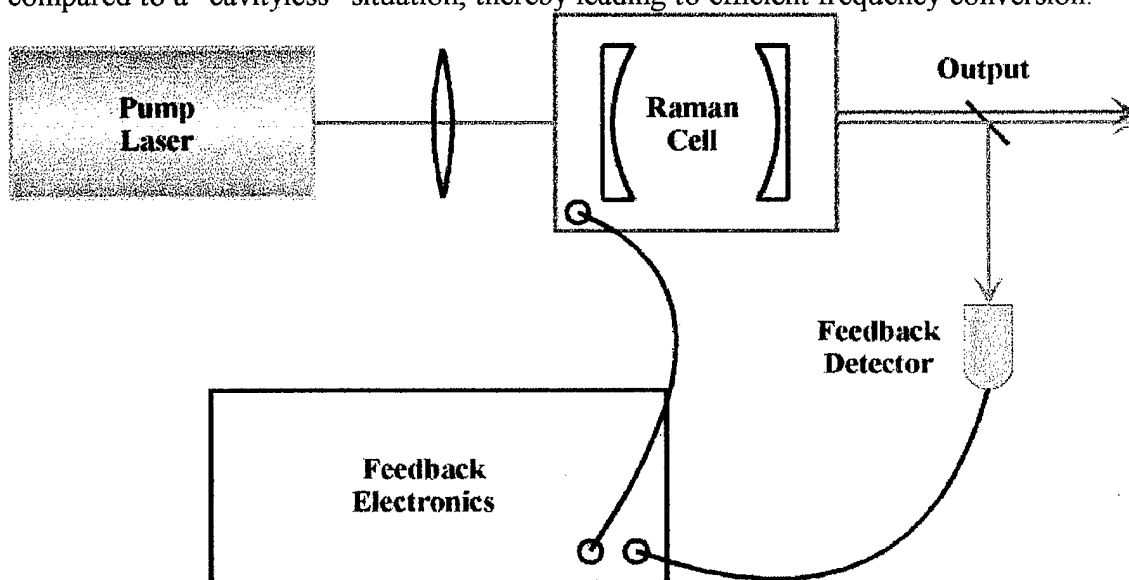

Figure 2. Schematic of cw Raman laser. A pump laser provides the energy to a Raman active material within a high-finesse cavity. A feedback system is required for efficient coupling of the pump laser into the Raman cell.

As evidence of the importance of this new laser, three independent companies have expressed an interest in partnering with AdvR on its development, and there has been additional interest from potential end-users in the research community. The companies expressing an interest in partnering in this development are Unisearch Associates, an international company largely devoted to environmental monitoring, Redcone Research Inc., a small company developing an instrument to provide real-time monitoring of laser eye surgery, and Spectra Physics, one of the largest manufacturers of lasers in the United States. Details of the partnering agreements with these companies will be spelled out in the Phase II proposal.

In conclusion, the cw Raman laser has been demonstrated to perform at high efficiencies and its performance is well modeled by code developed during this effort. A broad range of output powers are possible and a wide range of spectra can be accessed.

The importance of this laser is evident from the considerable interest from both potential end-users and commercial companies.

b. Project Objectives

The objective of the proposed Phase I effort was to demonstrate the feasibility of generating laser beams in the near- to mid-IR with powers of at least 1 Watt using a diode pumped cw Raman laser. Recent work done in the laboratories of Prof. John Carlsten at Montana State University has demonstrated that cw Raman lasers are a promising new technology.[1-5] The significant differences between the work done in Prof. Carlsten's laboratories and this effort were the target wavelengths and the pump laser characteristics. This first cw Raman laser operated at relatively low powers and used a 532 *nm* pump laser. For this effort, target wavelengths were chosen to match available high-power, high-beam-quality pump lasers. The specific objectives of this effort as set forth in the Phase I proposal are listed below.

I. **The pump laser requirements for a cw Raman laser that provides powers approaching 1 Watt will be established. The Raman cell requirements will be determined.** The characteristics of the Raman cell affect the coupling with the pump laser and determine the overall efficiency of the device. The key parameters for the Raman cell are the reflectivities of the high-finesse cavity mirrors at the pump and Stokes wavelengths, the free-spectral range, and the gas pressure.

II. **The optimal frequency locking mechanism will be identified.** A frequency locking system must be employed to insure that the pump laser is resonant with the high-finesse cavity within the Raman cell. To maintain this locking, one may wish to tune the pump laser, the high-finesse cavity, or both. The time responses of the pump laser and the high-finesse cavity are important factors in determining the best line-locking mechanism.

III. **The cw Raman's performance will be predicted based on sub-system component capabilities.** A proof-of-principle experiment with the cw Raman laser is not feasible in a six-month period, largely due to the time required for machining and customized mirror coating runs. However, the performance of available components can be determined from published accounts and vendor specifications. With these component capabilities, the cw Raman laser's performance will be predicted using code developed by AdvR. Results from this code will be compared with results from the first cw Raman laser.

IV. **Preparations for Phase II implementation will be made, including a design for a cw Raman laser that will meet the target specifications.**

Although the stated objectives were targeted towards utilizing high-power, diode lasers as pump lasers, including low-power pump sources and non-diode laser pump sources was easily included. This is important because there are a variety of important wavelengths that can be obtained using non-diode laser pumps. Additionally, there are

many wavelengths that can be accessed with the cw Raman laser at low powers that are of considerable importance for both commercial and research end-users.

c. Work Performed

This section on the work performed is organized to match the objectives from the previous section. Some of the work performed applies to more than one of the objectives. A short summary of the work done is provided for each objective, followed by a more detailed description.

Work performed to address Objective I: Determine the fundamental working requirements of the cw Raman laser.

1. Basic requirements of the pump laser were determined.
2. High-finesse cavity and Raman medium requirements determined.
3. Theory and numerical code was developed for steady-state modeling.
4. Theory and numerical code was developed for time-dependent modeling.

Pump laser requirements. For the cw Raman laser to function efficiently, the pump laser must be efficiently coupled into the high-finesse cavity containing the Raman active medium. The requirements for efficient coupling into a high-finesse cavity are dependent on the finesse of the cavity (determined largely by the reflectivity of the mirrors), the free spectral range of the cavity (determined by the length of the cavity), and on the focusing properties of the cavity (determined by the curvature of the mirrors and the length of the cavity).

Using the quantities above, the requirements on the pump laser were determined for efficient coupling. The results are that for optimal coupling the pump laser should operate in a single longitudinal and a single spatial mode. This is discussed more fully in the results section.

A second requirement on the pump laser is its power. The power output at the Stokes wavelength is directly related to the input pump power by the equation:

$$Stokes = Pump \times Efficiency \times \frac{\lambda_P}{\lambda_S}. \tag{1}$$

In addition to the direct dependence on the pump power indicated above, the efficiency of a cw Raman laser is dependent on the pump power. This dependency can be determined from the numerical code discussed below. Thus, the Stokes power does not scale linearly with the pump power. Theoretical results are shown below.

High-finesse cavity and pressure requirements. There are trade-offs in the optimal design for a cw Raman laser between the length of the Raman cell and the gas pressure. For compactness and simplicity, one would prefer a very small cell with a very low pressure. If this is done, one would find that the cw Raman laser would operate only in a few very precise situations. To make the laser operate easily, the cw Raman cell must have a reasonable length and pressure. The required balance for the parameters affected by the cavity length and gas pressure are the input pump bandwidth, medium depletion, and the Raman linewidth. In brief, one finds that a cell length of 5 *cm* and a gas pressure

around 70 *atm* (using hydrogen) will suffice for most applications. Further details are provided in the results section of this report.

Steady-state modeling. A steady-state model for the cw Raman laser was worked out[2,3] and numerical code was written in Mathcad™ to model the performance of the cw Raman laser. For a given set of cw Raman laser parameters, this model predicts the output Stokes power, reflected and transmitted pump power, and photon conversion efficiency as a function of input pump power.

The model was developed using standard Fabry Perot and steady-state stimulated Raman scattering theory. The input quantities to this model include: gas type and pressure; mirror radius of curvature; mirror reflectivity; mirror absorption/scattering loss; cavity length; and pump wavelength. A useful feature of this model is that it predicts the optimal pump laser powers and the cw Raman laser threshold. This program will provide the primary results needed to design cw Raman lasers. Additional results from the steady-state model are provided in the results section of this report.

Time-dependent modeling. A time-dependent model of the cw Raman laser was worked out[4] and numerical code was written in Mathcad™ to model the time-dependent behavior of the cw Raman laser. This code provided a check on the steady-state model. However, its chief function will be to provide modeling of the time-dependent behavior of the cw Raman laser where the laser is tuned from one frequency to another on a rapid time scale. In brief, tuning rates of the laser typically must be slower than the tens of kilohertz range to allow for the relatively long build-up times required for the high-finesse cavity. Additional results of the time-dependent model are given in the results section of this report.

Work performed to address objective 2: Identify the optimal frequency locking mechanism.

1. Suitable optical locking techniques were identified.
2. All-optical and Pound-Drever techniques.
3. Edge-locking circuit was designed, fabricated, and tested.

Suitable techniques identified. A fundamental requirement for the cw Raman laser is to couple the pump laser power into the high-finesse cavity containing the Raman active material. To do this, the pump laser must be frequency "locked" to the cavity. Suitable locking techniques were sought, and three techniques were identified.

The three frequency locking techniques are an all-optical locking technique, the Pound-Drever technique[6], and edge-locking. All three locking techniques were examined, each of which will likely find cw Raman laser applications. The all-optical technique relies on optical feedback that passes through the high-finesse cavity to frequency lock a diode laser. This technique in many ways is the most elegant, but it will not work with all lasers. The Pound-Drever technique utilizes an electro-optic modulator and is very precise in its locking. The edge-locking technique has the advantage of simplicity. All of these techniques are discussed in more detail in the results section.

All-optical and Pound-Drever techniques. The all-optical and Pound-Drever techniques are being used and developed in the laboratories of Prof. John Carlsten at Montana State University. Our approach has been to monitor their progress and learn

from them. These two techniques are summarized in the results section of this report. A close working relationship between AdvR and the Carlsten group has been established, and the Carlsten group has agreed to work with us if one of these two techniques is to be utilized.

Edge-locking technique development. With the edge-locking techniques, the pump laser and the Fabry Perot are locked to the edge of the transmission profile of the Fabry Perot interferometer. The feedback electronics can be used to control either the pump laser or the Fabry Perot.

Although the Phase I effort was designed to be a paper study, the scope and expense of developing an edge-locking detection system was small enough that it was pursued. Locking electronics were designed, fabricated, and packaged. Using an existing Fabry Perot interferometer, the edge-locking technique was tested with a single-mode diode laser, and later with a single-mode Argon Ion laser. Edge-locking has the advantage of simplicity and ease of implementation. Additional information on edge-locking is provided in the results section of this report.

Work performed to address objective 3: Predict the cw Raman laser's performance based on sub-system component capabilities.

1. Obtain estimates for available mirror technology.
2. Survey laser companies for appropriate pump lasers.
3. Use numerical code to determine output characteristics based on mirror and pump laser characteristics.

Determine current state-of-the-art in mirrors. The cw Raman laser is critically dependent on the reflectivity and loss from the mirrors used in the high-finesse cavity. With the advances in mirror technology, particularly ion sputtering, extremely high reflectivities are possible with very low losses. This, perhaps more than anything else, has been the enabling technology for the cw Raman laser.

Most of the effort devoted to these high-performance mirrors has been at visible and near-IR wavelengths. Much of the interest in the cw Raman laser is that it is capable of providing mid-IR wavelength laser radiation. A portion of this effort was devoted to identifying vendors who could provide high-performance mirrors at all wavelengths, with special emphasis on the mid-IR. Since there has been little to no demand for mirrors in the mid-IR, there are few vendors willing to make quotes in this spectral regime. Additional discussions on mirrors are included in the results section of this report.

Survey suitable pump lasers. A survey of suitable pump lasers for the cw Raman laser was made, with special emphasis on diode lasers. In addition to using this to map out the potentially achievable wavelengths, as shown in figure 1 of this report, suitable pump lasers that can provide high powers were also identified. The particular requirements on the pump laser are that it must be able to operate in a single longitudinal mode and a near-single spatial mode. A short list of potential high-power pump lasers is given in the results section of this report.

Model cw Raman laser with available components. The performance of a cw Raman laser was modeled using the values quoted for available components. One of the

primary goals of this effort was to develop the code for this application. The results from several runs of the numerical code are given in the results section of this report.

Work performed to address objective 4: Prepare for Phase II implementation and design a cw Raman laser to meet target specifications.

1. Design Raman cell.
2. Develop line-locking mechanism.
3. Modify Argon Ion laser for preliminary experiments.
4. Obtain existing Fabry Perot mount suitable for Raman cell.
5. Initiate industrial partnering arrangements.

Design Raman cell. A Raman cell was designed to accommodate an existing Fabry Perot interferometer. Although this design will not be optimal for some applications, it will be useful as a prototype device to demonstrate a high-power cw Raman laser. In particular, the cell was designed for a 488 *nm* Argon Ion pump laser with single-mode powers in excess of 1 *W*. To date, no cw Raman laser has been operated with pump powers this high. The cell design made for this application can also work at other wavelengths, and perhaps more importantly, it provides a starting point for the development of more compact designs. Specifics of the cell design are given in the results section of this report.

Develop tuning mechanism. As discussed above, an edge-locking technique was developed that will be used to frequency lock the Fabry Perot interferometer transmission profile to the Argon Ion laser frequency.

Modify Argon Ion laser. AdvR had an existing Argon Ion laser that produced approximately 7 *W* operating on all the Argon Ion laser lines. Inserting a new mirror set and an etalon modified this laser so it will operate on a single longitudinal mode at 488 *nm*. In this mode, the laser produces approximately 1.5 *W*. This laser will now be an effective pump laser for a cw Raman laser that will produce an output at 612 *nm*.

Obtain Fabry Perot cell for cw Raman laser. An essential component of the cw Raman laser is a high-finesse cavity. To line-lock the laser to the cavity, either the laser or the cavity must be tunable. In this case we obtained a used Burleigh Fabry Perot with PZT control that allows for cavity tuning. By inserting appropriate mirrors into this device, using the edge-locking electronics, and inserting the device into a high-pressure gas cell with windows, most of the cw Raman laser can be assembled. AdvR has initiated the actual fabrication of a cw Raman laser to further its development. The mirror, materials for the Raman cell, and gas pressure components have been ordered or will be shortly.

Initiate industrial partnering arrangements. AdvR has initiated partnering arrangements with two industrial partners. Redcone Research has agreed to incorporate the cw Raman laser into the real-time eye-profiler it is developing and Spectra Physics has agreed to supply a pump laser for Phase II investigations. Additionally, Unisearch Associates has expressed an interest in partnering with AdvR on the development of the cw Raman laser in the mid-IR spectral regime. Formalized arrangements will be put in place before a Phase II proposal is submitted.

d. Results Obtained

To make this report as readable as possible, the essential results are "bulletized," with supporting comments given below.

Working requirements of the cw Raman laser.

Pump laser requirements.

- The pump laser must operate in a near single-mode both spatially and temporally.

The acceptance bandwidth ΔB of the cw Raman laser is given by the free spectral range of the cavity divided by the finesse $\Im$.

$$\Delta B = \frac{c}{2L}\frac{1}{\Im} \tag{2}$$

where c is the speed light and L is the length of the cavity. A reasonable cavity length is on the order of 5 cm, and finesses of high-finesse cavities are on the order of 10^4. Using these numbers, one finds that the acceptance bandwidth $\Delta B \approx 300$ kHz. Many lasers have linewidths this narrow or narrower, but for two separate longitudinal modes of a laser to be within this bandwidth, the laser would have to have a length of at least 500 m. This long length clearly indicates that a multiple longitudinal mode laser is not practical.

Additionally, the pump laser must operate in a near single spatial mode. The reasoning for this is as follows. The high-finesse cavity is a non-confocal design. This has the advantages that the spot size within the cavity is always at or near focus, and the cavity is quite stable. However, using standard spatial beam mode analysis,[7] one finds that the higher order spatial modes within the cavity have different resonant frequencies than the lowest order spatial mode. For the geometry of a typical cw Raman laser, the frequency separation between the spatial modes Δf is approximately

$$\Delta f \cong \frac{c}{2\pi z_0} \tag{3}$$

where z_0 is the confocal beam parameter, which is much larger than the mirror spacing for the non-confocal design of the cw Raman laser. Because the higher order spatial modes will not be resonant with the high-finesse cavity when the lowest order mode is resonant, they will not be coupled into the cavity, and consequently all the laser power in these modes is wasted. Therefore the cw Raman laser will run best in a single spatial mode.

- Mirror reflectivities are critical in determining cw Raman efficiency.

As noted above, the power output at the Stokes wavelength is related to the input pump power by the equation:

$$Stokes = Pump \times Efficiency \times \frac{\lambda_P}{\lambda_S}. \tag{4}$$

The numerical code developed to model the cw Raman laser clearly shows that to optimize the efficiency of the cw Raman laser, the pump laser power must be known to

determine the optimal mirror properties. One can see this effect by examining figures 3 and 4.
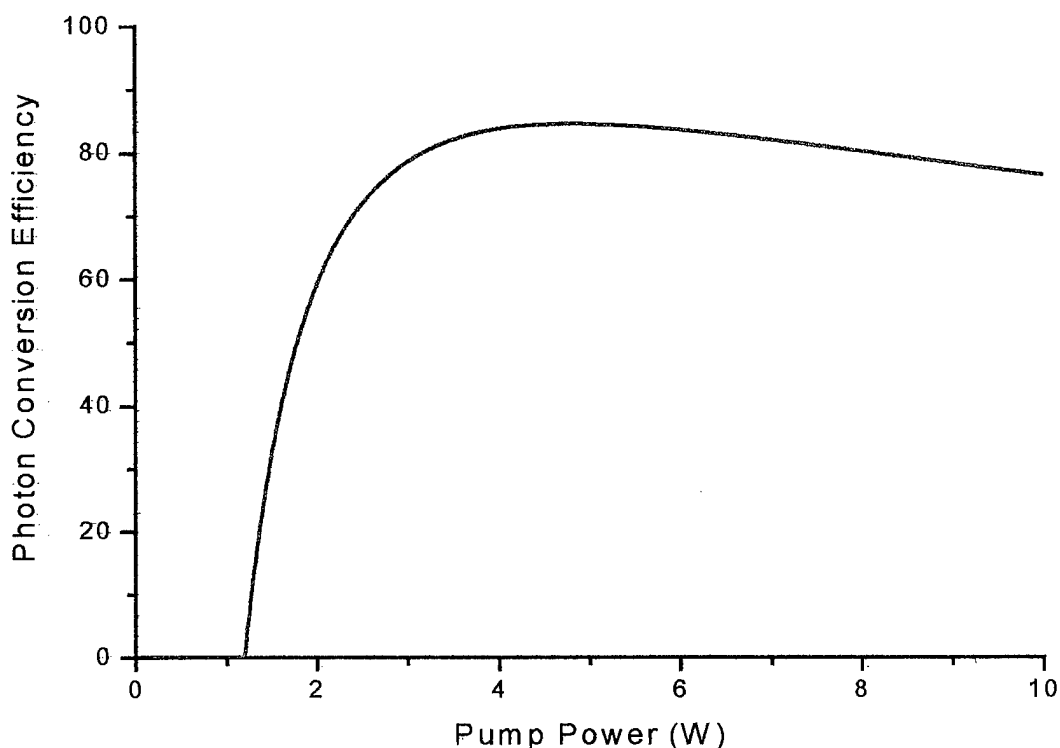

Figure 3. Photon conversion efficiency as a function of input pump power. The mirrors reflectivities are: R_F=.997 R_B=.9995 for the front and back mirrors at the pump wavelength and: R_F=.9995 R_B=.997 for the front and back mirrors at the Stokes wavelength. The absorption loss for all mirrors is A=15 *ppm*.

In figure 3, note that the peak efficiency occurs at a pump power of just under 5 *W*. However, if the mirror reflectivties are changed, as shown in figure 4, the peak photon conversion efficiency is shifted to just over 2 *W*. Here the mirrors are somewhat more reflective, with the last significant figure increased by 1 for each value. The mirror reflectivities are well within the current state-of-the-art capabilities. In fact, using current state of the art mirrors with very high reflectivities peak efficiencies in the milli-Watt regime can be achieved with the cw Raman laser. These two examples were chosen to demonstrate the critical importance of matching the pump laser power to the mirror characteristics to optimize efficiency.
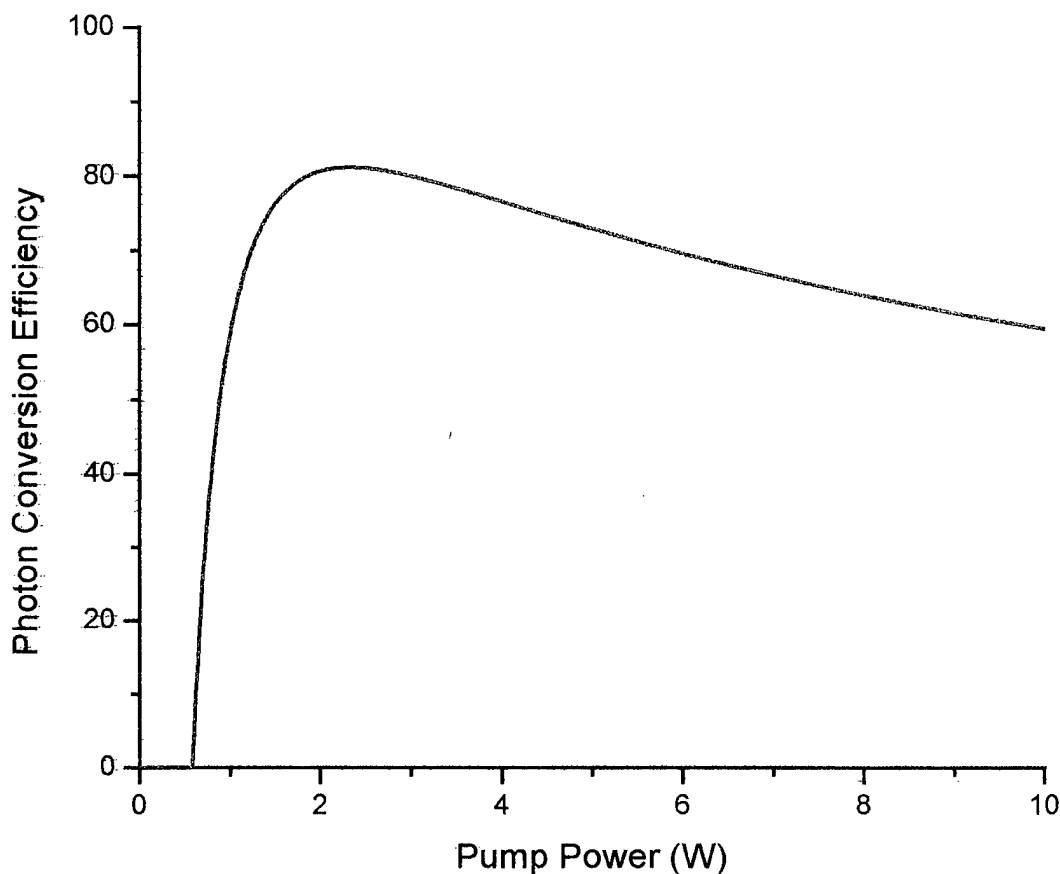
Figure 4. Photon conversion efficiency as a function of input pump power. The mirrors reflectivities are: $R_F = .998$ $R_B = .9996$ for the front and back mirrors at the pump wavelength and: $R_F = .9996$ $R_B = .998$ for the front and back mirrors at the Stokes wavelength. The absorption loss for all mirrors is $A = 15$ *ppm*.

<u>High-finesse cavity and pressure requirements.</u>

- A cavity length of 5 *cm* and a pressure of 70 *atm* is appropriate for a typical cw Raman laser.

The factors that go into the determination of the cavity length and gas pressure are practicality, the free spectral range, the Raman linewidth, and medium depletion considerations. For practicality, a length of 5 *cm* was chosen; longer or shorter cavities could be used, but this length is likely to be close to the length chosen for most cw Raman lasers.

A cw Raman laser must be resonant at both the pump and Stokes wavelengths. Ideally, the Raman gain will be maximized at a mirror spacing at which the pump is resonant with the cavity. This will typically not occur, as diagramed in Figure 5, where one sees that the blue sine wave (pump) has a minimum at both mirrors, but the red sine

wave (Stokes wavelength with maximum gain) does not. Thus, the blue wave is resonant, but a cavity of a different length would be required for the red wave to be resonant. The lengths were the red and blue waves are resonant is indicated in the plot below the sine waves in Figure 5.
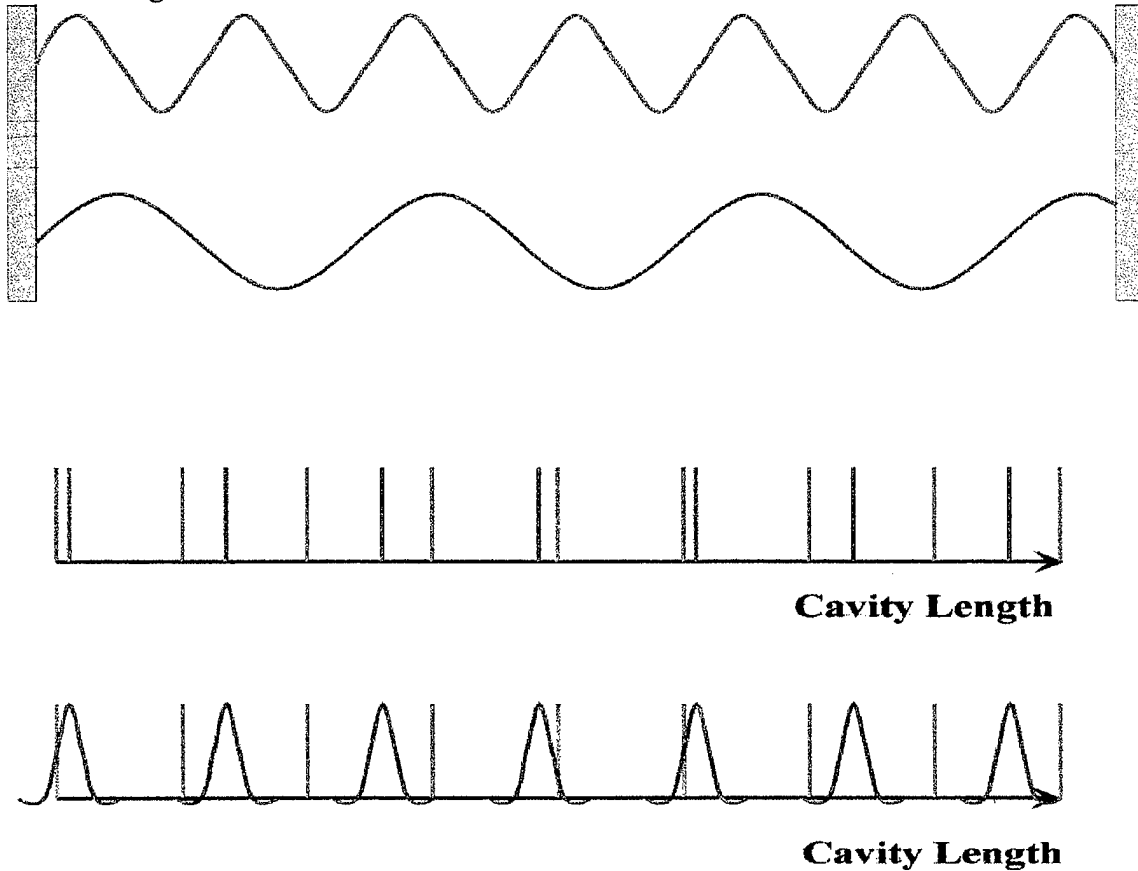

Cavity Length

Cavity Length

Figure 5. Diagram exhibiting the double resonance condition. Typically a perfect double resonance will not be achieved at the maximum gain for Raman scattering. Fortunately, the Raman linewidth is broad enough that there will be sufficient gain for resonant Stokes radiation.

The worst-case scenario will have the peak of the Raman gain half of a free spectral range from the cavity mode at which the laser will want to operate. Even in this worst case scenario, efficient Raman scattering can occur if the linewidth of the Raman gain is broad, as indicated by the lowest plot in Figure 5. For a cavity 5 *cm* long, the free spectral range $\frac{c}{2L}$ is 3 *GHz*. Thus, the Raman gain should have a linewidth of approximately 3 *GHz* to allow for significant gain at the resonant frequency.

The Raman linewidth Δv in hydrogen at room temperature is given by [8]

$$\Delta v = \frac{309}{\rho} + 51.8\rho \tag{5}$$

where Δv is in *MHz* and ρ is the density in amagats. To obtain a linewidth of 3 *GHz*, a pressure of approximately 70 *atm* is required. Although this pressure is rather large, the volumes required are very small, thereby greatly diminishing the danger of explosion.

Because there is strong coupling between the various vibrational modes of methane, it has a linewidth broader than 3 *GHz* even at moderate pressures, and consequently, lower pressures can be used.[9]

The other factor that plays a role in the pressure considerations is medium depletion. If one calculates the number of molecules in the pump beam volume within the high-finesse cavity and divides this by the relaxation time for hydrogen, the number of molecules available per second is achieved. We could not find precise values for this time constant at 70 *atm*, but it is known that the time constant is no larger than 10 *μs*.[10] If one assumes that 5 *W* of Stokes radiation is being produced at 1.5 *μm*, an ambitious number, there are still more than 10^4 molecules available per photon. Thus, one concludes that even when the cw Raman laser is operating at very high powers, medium depletion is not a serious factor.

<u>Steady-state modeling.</u>

- Numerical code based on a steady state theory supplies important operating parameters.

A steady-state model for the cw Raman laser was worked out and published by the John Carlsten group at Montana State University.[2,3] This model has been shown to model the experimental results obtained from a cw Raman laser extremely well.[2,4] Using this model, and incorporating the frequency dependent Raman linewidths for hydrogen[8] and methane[11], numerical code for the cw Raman laser was written. Results of this model were compared to those from the Carlsten group. Results from this code that predict the cw Raman laser photon efficiency are shown in figures 3 and 4. Other important results that are obtained with this code are the pump power reflected from the cw Raman laser, the pump power transmitted through the cw Raman laser, the Stokes power emitted from the cw Raman laser, and the cw Raman threshold, all as functions of the input pump power. An example of these results is shown in figure 6.
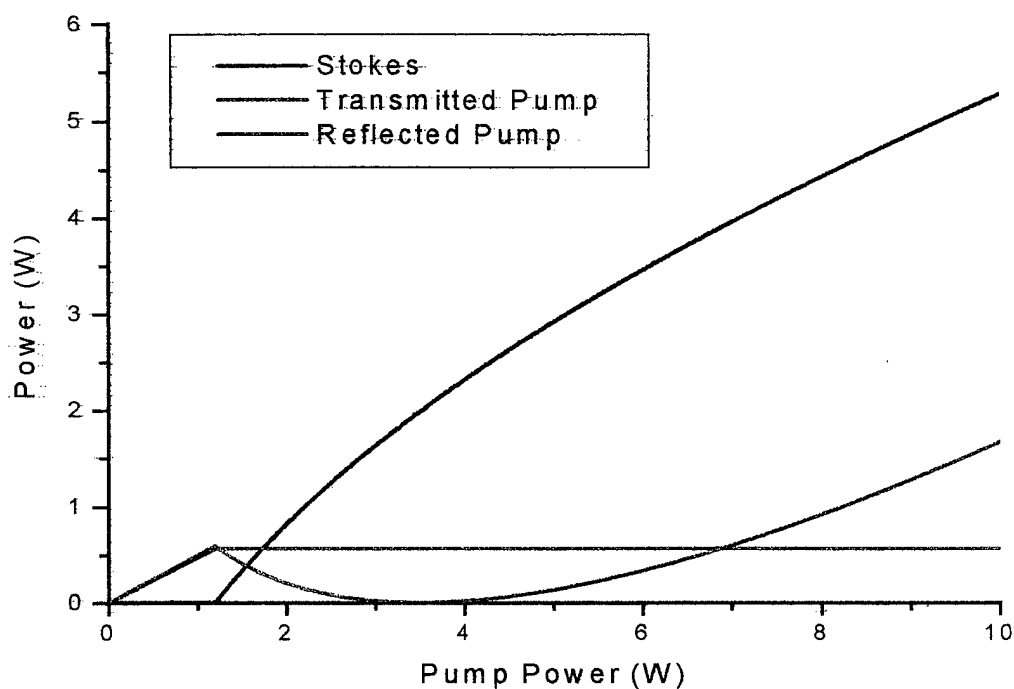
Figure 6. Theoretical results of the reflected pump, transmitted pump, (1.064 *μm*) and Stokes (1.54 *μm*) power as a function of input pump power from a methane cw Raman laser. The cw Raman laser has a cavity length of 5 *cm* and mirror reflectivities of: R_F=.997 R_B=.9995 for the front and back mirrors at the pump wavelength and: R_F=.9995 R_B=.997 for the front and back mirrors at the Stokes wavelength. The absorption loss for all mirrors is A=15 *ppm*.

An important point to note is that the theoretical modeling has been found to be in excellent agreement with this steady state model.[2,4] This is shown in figure 7, where experimental data on the cw Raman laser output is plotted with the theoretical results from the steady state theory. This data was taken by the John Carlsten group.[13]
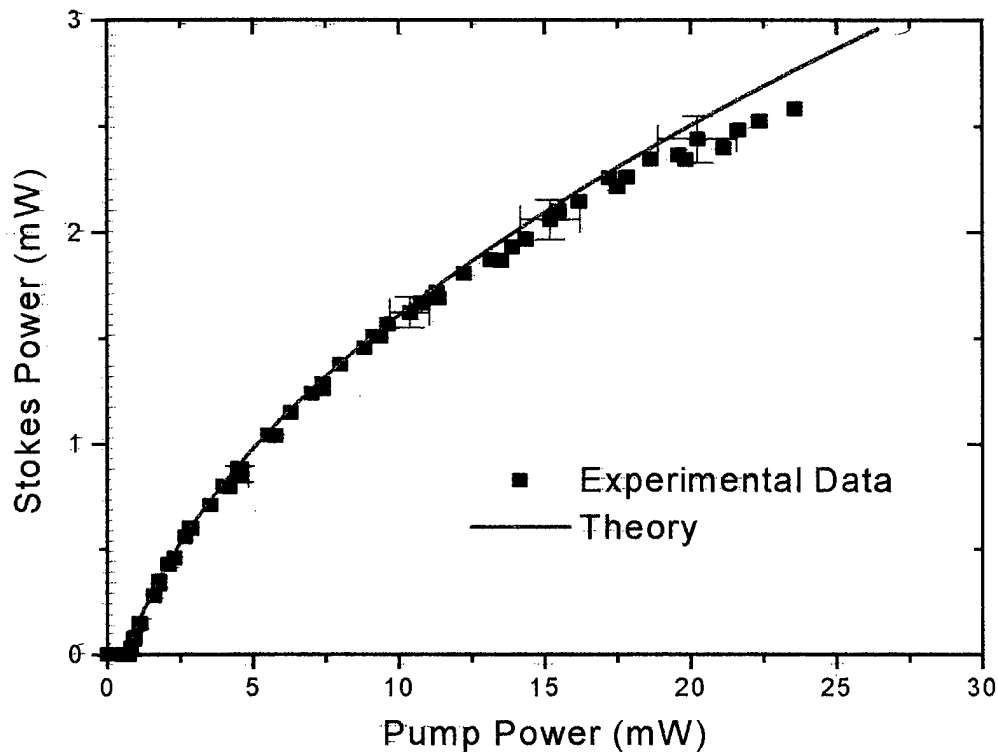
Figure 7. Experimental data plotted with theoretical results from the steady state theory. Note the excellent agreement.

Time-dependent modeling.

- Time dependent modeling provides information useful for determining tuning rates.

Following the work of Brasseur *et. al,* [4] a time-dependent numerical model of the cw Raman laser was made using Mathcad™. There have been some experimental results on oscillations associated with locking electronics for which this model has exhibited success.[4] However, experimental results on the actual turn-on and turn-off behavior of the cw Raman laser have not been obtained. Never the less, the time-dependent model provides the current best information available on the turn-on and turn-off behavior of the cw Raman laser. The importance of this is that the turn-on behavior in particular must be understood to determine the rates at which the laser can be tuned from, for example, on-line to off-line for spectroscopy applications. Results of this work indicate that the turn-on times are typically in the range of 1 μs to 10 μs, depending primarily on the reflectivities of the mirrors. An example of the turn-on behavior of a cw Raman laser is shown in figure 8.
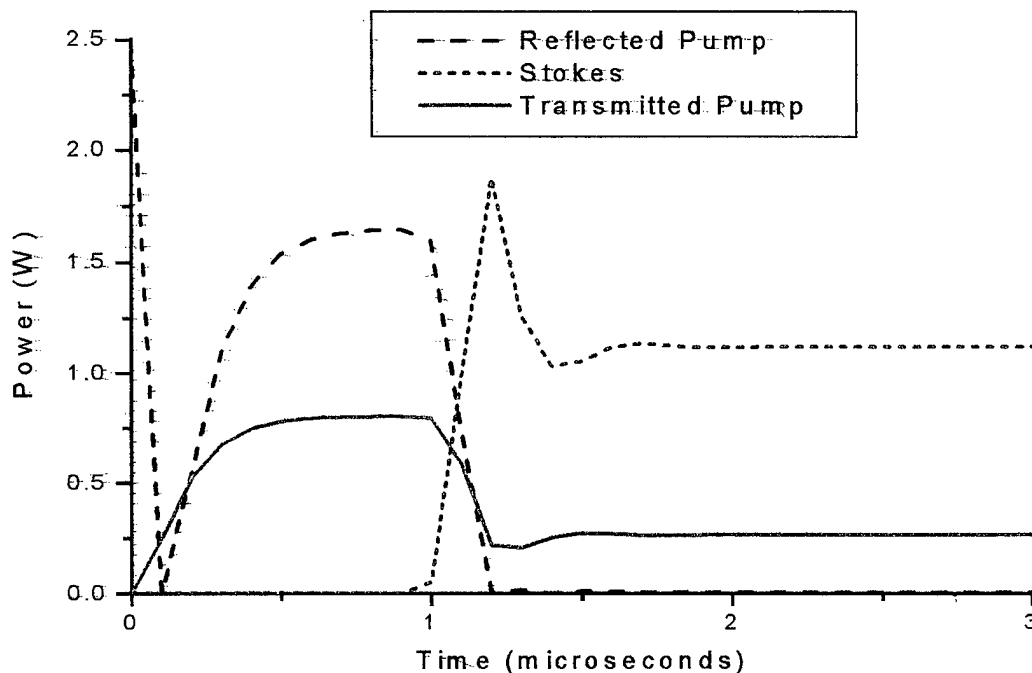
Figure 8. Time dependent behavior of a cw Raman laser. The time evolution of the pump reflected from the high-finesse cavity, the transmitted pump, and the Stokes is shown. In this case, a 2.5 W pump laser with a wavelength of 1.064 μm is assumed with a methane cw Raman laser.

In figure 8, note that the laser exhibits a few damped relaxation oscillations before settling into steady-state within 2 μs. Because the high-finesse cavity has such a long time constant, one finds that relaxation oscillations are typically damped out quickly. One can see that the reflectivities chosen for the results in figure 7 yield excellent impedance matching in that the amount of steady-state pump that is reflected is extremely small. The code used to generate these results can be used to predict turn-on times for cw Raman lasers in general.

Identify the optimal frequency locking mechanism.

Suitable techniques identified.

- Pound-Drever technique.

The Pound-Drever technique[6] has been employed on the first cw Raman laser constructed.[1] One of the primary advantages of this technique is that it provides very precise locking. A significant disadvantage of the Pound-Drever technique is that it requires an external electro-optic modulator and associated driving electronics if the pump laser beam cannot be directly frequency modulated.

The Pound-Drever technique utilizes a Frequency Modulated (FM) pump laser beam. The FM beam has identical side-bands equally spaced in frequency on either side of the main carrier frequency. The beating between the lower side-band and the dominant central frequency component is exactly out of phase and matched with the beating of the central frequency component with the upper side-band. Consequently, and ideal FM beam exhibits no amplitude modulation.

When this beam is input to the high-finesse cavity, the phase of the reflected central frequency component is shifted unless it is exactly on resonance. This shift will unbalance the beating between the central frequency component and the upper and lower side-bands, leading to amplitude modulation. Additionally, the relative phase of the amplitude modulation leads to a sign difference between the above resonance and below resonance situation. Consequently, the amplitude modulation of the pump signal reflected from the high-finesse cavity provides a useful error signal to control the locking of the pump laser to the cavity.

The Carlsten group has fabricated a dedicated circuit board for the electronics of the Pound-Drever technique that has worked well. Since AdvR has a close working relationship with the Carlsten group, our approach has been to utilize this expertise.

- Edge-locking technique.

The edge-locking technique works by stabilizing the transmission through a Fabry Perot interferometer. An advantage of this technique is its relative simplicity. A disadvantage of the technique is that the frequency locking is not as precise as the Pound-Drever technique and one can not lock to the center of the transmission profile.

Ideally, one would like to lock to the peak of the transmission, but if this is attempted, the electronics can not tell which way to adjust the frequency when a drift occurs because a drift in either direction from resonance decreases the transmission. That is, there is no "directional" information available if one attempts to lock to the peak. However, if one locks to the edge of the transmission profile, directional information is obtained with a frequency shift because a shift in frequency downward has the opposite effect on the transmission as compared to a shift in frequency upwards.
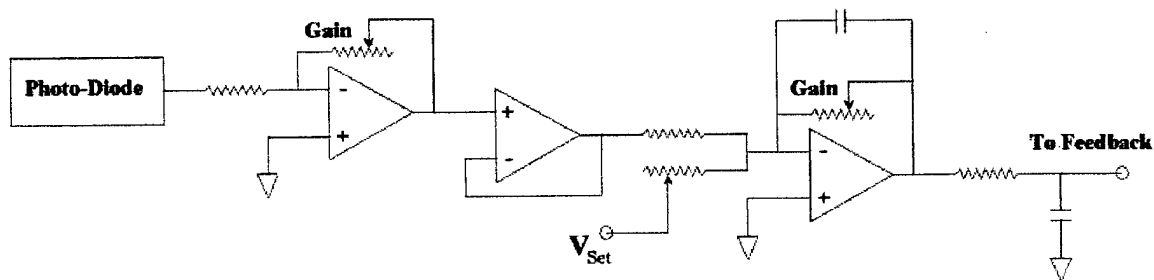

Figure 9. Basic schematic of edge-locking electronics.

The edge-locking electronics consist of a photo-diode, which is amplified with the first operational amplifier. The output signal is buffered before being input to a second operational amplifier. An adjustable set-point voltage is added to the input to determine how "high" on the transmission profile of the Fabry Perot interferometer the circuit is set.

The output of the circuit is fed to a PZT controller that adjusts the spacing of the mirrors within the cavity.

This circuit has been assembled and tested, yielding good locking. Current plans are to utilize this circuit with a prototype cw Raman laser that utilizes at 1.5 W Argon Ion laser (488 nm) as a pump.

- All-optical locking.

The all-optical locking technique is the most elegant of the locking techniques examined during this effort. This technique takes advantage of the transmission profile of the high-finesse cavity to provide a direct optical feedback to the laser source. Although this technique is elegant, it has the disadvantage that it will only work with pump laser sources that can be locked with a small amount of optical feedback. Fortunately, this technique works well with diode laser sources. A schematic of the all-optical locking technique is shown in figure 10.
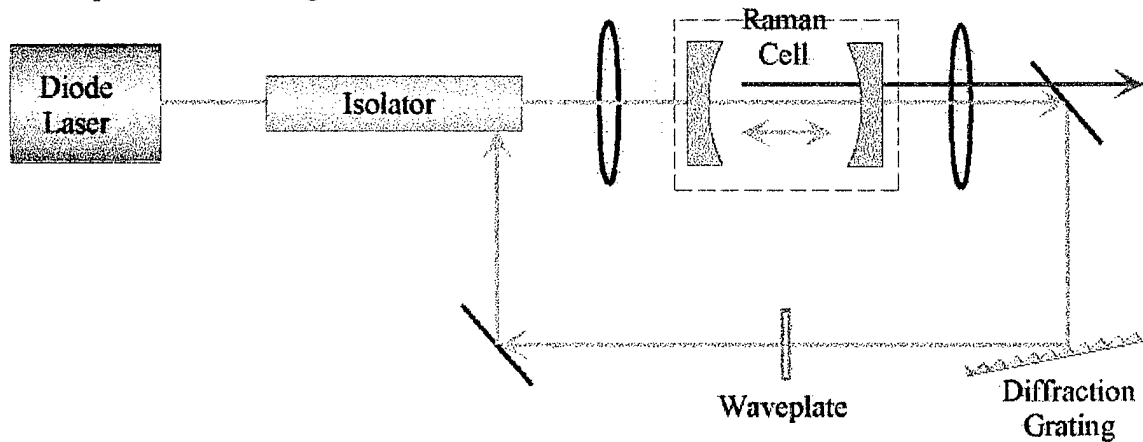
Figure 10. Schematic of the all-optical locking cw Raman laser developed in the laboratories of Prof. John Carlsten at Montana State University.

The technique works as follows. An Anti-Reflection (AR) coated laser diode pumps a cw Raman laser through an isolator. The isolator eliminates the radiation reflected from the high-finesse cavity. Since only resonant radiation passes through the high-finesse cavity, it is fed back to the diode laser for locking. A diffraction grating is used to select a single longitudinal mode, and a waveplate is used to orient the polarization of the feedback such that it couples efficiently back to the diode pump laser.

This technique has been used with a 790 nm pump to produce 15 mW of Stokes radiation at 1180 nm with a 60% photon conversion rate.

Predict the cw Raman's performance based on sub-system component capabilities.

High-power components.

- High-finesse cavity mirrors

Currently, the best quality mirrors we know of for high finesse cavities are made using an ion sputtering technique. This technique is somewhat slow, and rather expensive, but the results are impressive. AdvR has surveyed three companies that specialize in high quality mirrors to determine what the state-of-the-art is currently. In particular, their capabilities in the near- and mid-IR were requested.

Research Electro-Optics (REO). REO will coat mirrors for wavelengths from the near UV to approximately 3.1 μm. At 1 μm they can obtain reflectivities of 0.99999, at 2 μm they quote 0.9999, and at 3 μm they can obtain 0.999. At this time, they are unwilling to consider best-of-effort attempts to coat for longer wavelengths. REO has supplied the mirrors for the cw Raman lasers fabricated in the Carlsten laboratories at Montana State University.

Laser Power Corp. Laser Power has coated mirrors from the visible to 7 μm. From 2 μm to 7 μm they quote a reflectivity of 0.9995. Additionally, they claim to have overcome the well-known water absorption problems that can occur at some important wavelengths. Coating runs typically cost between $15,000 and $25,000.

Coherent Optics Division. Coherent claims to routinely make mirrors through the entire range from 1 μm to 5.5 μm, but they did not provide exact reflectivities.

- High-power pump lasers.

As noted above, the pump laser for a cw Raman laser must be near single mode, both spatially and longitudinally. AdvR has conducted a survey of laser diode manufacturers to find out what wavelengths are available with near single mode pumps, and also what powers are available at those wavelengths. Since the laser industry as a whole, and the laser diode industry in particular, is changing rapidly, any survey is likely to be accurate for a short period of time at best. Examples of volatility include companies that simply disappeared to, in one case, finding a large company that would not admit they manufacture a laser even though we determined they sell them to the Air Force.

Although there are reports of high-power diode lasers at a variety of wavelengths, it is difficult to find many with single-mode powers as high as a Watt. In the table below, several lasers that are in the Watt regime are listed, along with the attainable Stokes wavelength. The actual amount of power in the dominant mode is not known for some of these lasers, although the 10 W Nd:YAG is specified to be single-mode spatially and longitudinally.

λ_P (μm)	P_P (W)	λ_S (μm)	Laser Type
0.935	2.5	1.53 (1.29)	Diode
0.98	5	1.65 (1.37)	Diode
1.064	10	1.91 (1.54)	Nd:YAG
1.1	9+	2.03 (1.62)	Fiber

Table 1: Potential pump lasers, their wavelengths, peak powers, and Stokes wavelengths using hydrogen (methane).

In addition to the high-power pump lasers noted above, it should be noted that there are numerous diode laser sources with a 100+ *mW* of power, and there are also solid state cw lasers that may prove to be useful pump lasers.

- High-power cw Raman laser based on existing components.

As noted above, it is easier to obtain high-reflectivity mirrors in the near-IR spectral regime than in the mid-IR. Since there is considerable interest in high-power eye-safe laser light, we have concentrated our modeling on using a Nd:YAG laser with methane as a Raman active material to get 1.54 μm laser radiation. Results of this modeling are shown in figures 3, 4, 5, and 7. The mirror reflectivities used in these simulations are considerably below the state-of-the-art.

Prepare for Phase II implementation and design a cw Raman laser to meet target specifications.

<u>Design Raman cell.</u>

A mechanical design for a Raman cell has been made. This cell has been designed to accommodate an existing PZT driven Fabry Perot interferometer manufactured by Burleigh. The cell has been designed such that for 70 *atm* of pressure, the walls have a safety factor of 5.5, the screws have a safety factor of 3.8, and the windows have a safety factor of 4. The mechanical drawings for the cell are shown in figure 11.
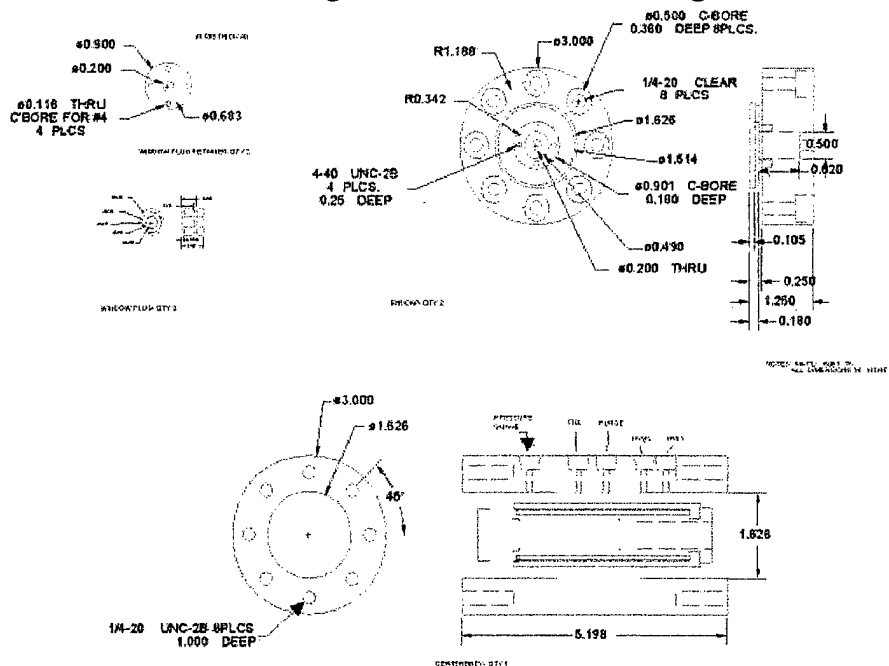

Figure 11. Mechanical drawings for a prototype cw Raman laser. Current plans are to use this design for an Argon Ion pumped cw Raman laser to demonstrate the feasibility of high-power cw Raman lasers.

<u>Develop line-locking mechanism.</u>

As has been discussed above, an edge-locking circuit has been designed, built, and tested. This circuit, shown in figure 8, will be used to lock the cavity to the 488 *nm* Argon Ion laser pump in the high-power prototype currently under development.

<u>Modify Argon Ion laser for preliminary experiments.</u>

AdvR had a *T W* Argon Ion laser at the beginning of this effort. This laser, however, ran in a multi-line mode that is not suitable as a pump for the cw Raman laser. To make this laser run on a single mode, the appropriate modification package has been purchased and installed, yielding approximately 1.5 *W* of single mode power at 488 *nm*. Using this laser to pump a cw Raman laser will provide an important test of the technology because no cw Raman laser to date has been pumped at powers above a Watt.

<u>Obtain existing Fabry Perot mount suitable for Raman cell.</u>

An existing Burleigh Fabry Perot interferometer has been obtained. High finesse mirrors will be installed in this device. The mirrors in the Fabry Perot are controlled via PZT actuators, which will be used to maintain frequency locking with the pump laser. Although the existing Fabry Perot design is not ideal for a commercial cw Raman laser, utilizing an existing Fabry Perot interferometer greatly decreases the expense of the prototype and will clearly demonstrate the technology.

<u>Initiate industrial partnering arrangements.</u>

AdvR is well suited to develop a prototype cw Raman laser. However, for commercial success, industrial partnering is critical. Therefore, AdvR has sought commercial partners and potential end users. Currently, three companies have expressed an interest. The three companies are Unisearch Associates, an international company largely devoted to environmental monitoring, Redcone Research Inc., a small company developing an instrument to provide real-time monitoring of laser eye surgery, and Spectra Physics, one of the largest manufacturers of lasers in the United States. Redcone Research Inc. wants to incorporate the cw Raman laser into a product line it is developing, and intends to purchase at least two lasers reasonably soon for testing. Spectra physics has agreed to provide a pump laser for Phase II investigations.

In conclusion, all tasks of the Phase I effort have been fully addressed, and additional work on the actual fabrication and development of a cw Raman laser has been initiated.

e. Estimates of Technical Feasibility

The technical feasibility of the cw Raman laser has, to a large extent, been established in the laboratories of Prof. John Carlsten. The first cw Raman laser put together in this laboratory achieved photon conversion efficiencies of 35%,[1] and since then efficiencies

of approximately 65% have been observed.[14] Additionally, the numerical modeling of the cw Raman laser has been found to be in excellent agreement with experimental results.[2,4]

To date, the cw Raman laser has been shown to work well in the visible to near-IR spectral regime, with output powers up to 15 mW. Because the cw Raman laser provides a high-quality laser beam, there will be numerous applications for the laser at the level it has been demonstrated. However, the range of possible applications will can be greatly increased by: 1) Expanding the demonstrated output wavelengths to longer wavelengths, particularly the mid-IR spectral regime; 2) Demonstrating high-power output from the cw Raman laser; 3) Engineering the laser so it will be able to operate in high-vibration environments.

The key enabling technology for the cw Raman laser is the development of very highly reflective mirrors that are manufactured using an ion sputtering technology. Results of this effort indicate that current mirror technology will allow the cw Raman laser to provide wavelengths from the visible to approximately 5.5 μm, depending on the pump laser characteristics. In principle, longer wavelengths are possible. It may also be possible to access long wavelengths by utilizing totally internal reflection techniques, but this approach is beyond the scope of this investigation.

Current efforts at AdvR are devoted to testing the cw Raman laser at higher powers than what have been demonstrated to date. In this effort, a 1.5 W laser beam will be used to pump a cw Raman laser. Theory indicates that there will be not problems with medium depletion and the mirrors will be able to handle the beam intensities, although there is some evidence that the reflectivities will decrease as the mirrors are heated. This effort will determine the importance of thermal effects within the Raman laser at high pumping rates.

The cw Raman laser has the potential to be built into a very compact system, small enough to fit in a person's hand. Designs this small have the potential to exhibit reasonable insensitivity to vibration. The John Carlsten group has conducted investigations on the stability of high finesse cavities to pressure and temperature variations,[15] and they are now interested in pursuing studies on vibrations, largely to address concerns relevant to the development of the cw Raman laser.

In conclusion, the cw Raman laser as it has been demonstrated is clearly feasible for numerous applications, as indicated by the interest from other commercial companies. Additionally, efforts are being made to expand the capabilities of the cw Raman laser that will make the laser suitable for an even broader range of applications.

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